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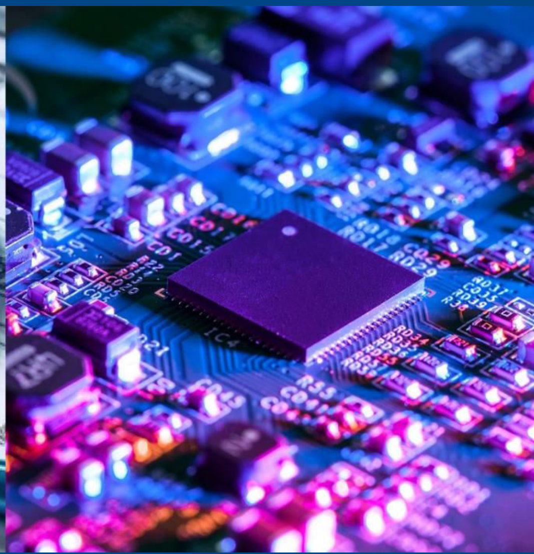

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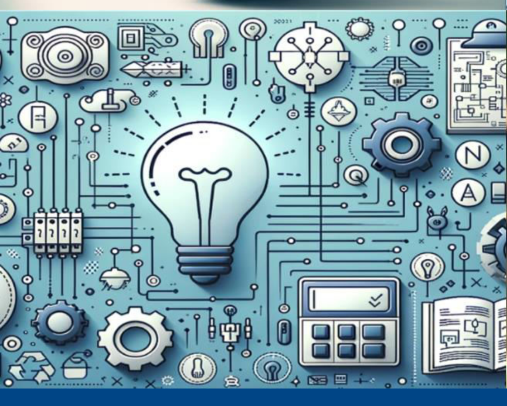

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Performance Evaluation of Alternative Binders in Concrete Without Cement

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ABSTRACT: Cement is a crucial binding agent in concrete and mortar, playing a significant role in the construction industry. However, its large-scale production is highly energy-intensive and contributes substantially to greenhouse gas emissions, impacting the environment. With cement manufacturing accounting for nearly 7% of global man-made carbon dioxide emissions, there is an urgent need to explore sustainable alternatives. Efforts are being made to reduce cement consumption by incorporating industrial by-products such as fly ash, silica fume, and ground granulated blast furnace slag. These materials, rich in amorphous silica, serve as effective mineral admixtures for partial cement replacement. Among them, fly ash binder presents a promising, eco-friendly alternative to conventional cement. Composed of aluminosilicate materials activated by an alkaline solution of sodium silicate and hydroxide, fly ash binder offers a sustainable solution with comparable strength and durability. Utilizing fly ash binder in concrete not only conserves natural resources but also enhances energy efficiency and reduces environmental impact. The mix proportions, based on ACI code guidelines, involve a complete replacement of cement with fly ash, leading to improved compressive strength. This innovative approach supports sustainable construction practices, promoting a greener and more resilient built environment.

KEYWORDS: Cement replacement, fly ash binder, sustainable construction, greenhouse gas emissions, energy-efficient materials

I. INTRODUCTION

In the contemporary world, construction plays a vital role in infrastructural development, serving as the foundation for urban expansion, transportation networks, and various engineering projects. Among the many materials used in construction, concrete remains one of the most essential components due to its durability, strength, and adaptability. Concrete is primarily composed of cement and aggregates, and its production relies heavily on natural resources. As infrastructure development continues to expand, the demand for cement and aggregates has grown exponentially, placing immense pressure on engineers and researchers to devise cost-effective and eco-friendly solutions that minimize environmental degradation while maintaining structural integrity.

One of the most widely used binders in concrete is Ordinary Portland Cement (OPC), a material that has been integral to the construction industry for centuries. However, the production of OPC is highly energy-intensive and environmentally damaging. The manufacturing process involves the calcination of limestone and the combustion of fossil fuels, which release large quantities of carbon dioxide (CO_2) into the atmosphere. Studies indicate that for every ton of OPC produced, approximately 600 kg of CO_2 is emitted. This significant environmental footprint makes OPC one of the largest contributors to global greenhouse gas emissions. Moreover, cement production requires vast amounts of energy, ranking second only to steel and aluminum in terms of energy consumption. Given these concerns, it is imperative to explore alternative materials that can effectively reduce the reliance on OPC without compromising the quality and performance of concrete.

One promising solution lies in fly ash, a byproduct generated from the combustion of coal in thermal power plants. Historically considered an industrial waste material, fly ash is now being recognized as a valuable resource for sustainable construction. The widespread availability of fly ash worldwide offers a unique opportunity to reduce dependence on traditional cement and mitigate environmental impacts. When fly ash is combined with alkaline activators, it undergoes a polymeric reaction, forming a stable and durable binder capable of replacing OPC in concrete production. This fly ash-based binder not only provides an eco-friendly alternative but also enhances the properties of concrete, including increased durability, reduced permeability, and improved resistance to chemical attacks.

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The adoption of fly ash-based concrete presents numerous environmental and economic advantages. Since OPC production accounts for approximately 85% of the total energy consumption and 90% of CO_2 emissions in typical ready-mixed concrete, replacing it with fly ash-based binders can lead to substantial reductions in carbon emissions. Additionally, utilizing fly ash in concrete reduces landfill waste, conserves natural resources, and promotes circular economy principles by transforming industrial byproducts into high-value construction materials. Given these benefits, the construction industry is increasingly exploring fly ash applications in transportation infrastructure, high-rise buildings, and other structural projects, aligning with global sustainability initiatives and paving the way for a greener, more resilient built environment.

II. LITERATURE REVIEW

Concrete is a fundamental material in the construction industry, primarily composed of cement, water, aggregates, and additives. However, cement production is a major contributor to global carbon emissions, accounting for nearly 8% of total CO_2 emissions due to the high energy consumption and chemical reactions involved in its manufacturing process. To mitigate these environmental impacts, researchers have focused on the development of cement-free concrete or concrete with reduced cement content. Alternative materials such as geopolymer concrete, fly ash-based concrete, slag concrete, and natural pozzolans have been extensively studied as potential replacements for traditional cement.

Geopolymer concrete has gained attention as an innovative and sustainable alternative to traditional cement-based concrete. Davidovits (1991) introduced geopolymer cement as an eco-friendly solution, wherein alumino-silicate materials, such as fly ash, slag, and metakaolin, react with alkali activators to form a durable binder. Research has demonstrated that geopolymer concrete can exhibit mechanical properties comparable to or even superior to conventional concrete. Bakharev (2005) found that fly ash-based geopolymer concrete achieved compressive strengths up to 40 MPa, which is on par with traditional Portland cement concrete. However, the strength and performance of geopolymer concrete are influenced by factors such as raw material type, curing temperature, and the concentration of alkali activators.

Fly ash, a byproduct of coal combustion in thermal power plants, is one of the most widely researched materials for partial or complete cement replacement. Studies have highlighted its beneficial effects on concrete workability and durability. Rashid et al. (2015) reported that fly ash enhances long-term strength development, although early-age compressive strength may be lower than that of conventional concrete. Similarly, Siddique (2011) found that replacing 30-40% of cement with fly ash resulted in compressive strength values comparable to those of standard concrete when appropriate curing techniques were applied. The delayed strength gain of fly ash-based concrete is attributed to its slower hydration process.

Ground Granulated Blast-Furnace Slag (GGBS) has been widely used as a sustainable binder due to its pozzolanic properties and ability to improve concrete durability. Sahu et al. (2012) investigated slag-based concrete and observed that it exhibits excellent resistance to aggressive environments and achieves good compressive strength, particularly with an optimal slag-to-cement ratio. The study emphasized that the compressive strength of slag-based concrete is highly dependent on the fineness of the slag and the curing conditions. Moreover, slag enhances the long-term performance of concrete, making it a suitable option for large-scale infrastructure projects.

Natural pozzolans, including volcanic ash, calcined clay, and rice husk ash, have been explored as alternative binders due to their ability to react with calcium hydroxide and produce cementitious compounds. Gambhir et al. (2009) studied the incorporation of rice husk ash in concrete and found that it contributed to increased compressive strength over time. Similarly, Bui et al. (2017) demonstrated that natural pozzolans, when used in conjunction with appropriate activators and curing conditions, significantly enhance concrete durability and strength. These findings support the viability of natural pozzolans as an environmentally friendly substitute for cement.

Despite the numerous advantages of cement-free concrete, several challenges must be addressed before its widespread adoption. One of the primary concerns is the variability in performance due to differences in raw material quality, mix proportions, and curing conditions. Additionally, the durability of cement-free concrete under long-term exposure to environmental factors, such as freeze-thaw cycles, sulfate attack, and alkali-silica reactions, remains a subject of ongoing research. Another critical issue is the workability of alternative binders, which may differ significantly from conventional cement, posing practical challenges in large-scale construction applications.

Research in cement-free concrete continues to evolve, with a focus on improving its mechanical properties and long-term durability. One promising approach is the development of hybrid binders that combine multiple materials, such as fly ash and slag or natural pozzolans with alkaline activators. Chen et al. (2019) explored blended geopolymer systems and found that they significantly enhanced both the compressive strength and environmental performance of concrete. Additionally, advancements in nanotechnology, such as the incorporation of nano-silica, have shown potential in enhancing the microstructure and mechanical properties of cement-free concrete. These innovations pave the way for more sustainable construction practices, reducing reliance on traditional cement while maintaining high-performance concrete standards.

The shift toward sustainable construction materials is crucial in reducing the environmental impact of concrete production. Geopolymer concrete, fly ash-based concrete, slag-based concrete, and natural pozzolans offer viable alternatives to conventional cement, with research demonstrating their potential to achieve comparable or superior performance. However, challenges related to material variability, durability, and workability must be addressed through further research and innovation. The continued development of hybrid binders and nano-enhanced materials will play a significant role in advancing the adoption of cement-free concrete in the construction industry.

III. METHODOLOGY

This research follows a systematic approach to replacing 100% cement in concrete with fly ash and chemical activators, specifically sodium silicate and sodium hydroxide, to evaluate its engineering properties and performance. The study began with a comprehensive literature review to assess the feasibility of cement-free concrete. Based on previous research, fly ash was chosen as the primary binder, while sodium hydroxide and sodium silicate were selected as activators. Additional materials, including coarse aggregate (20 mm), fine aggregate (M-sand), and distilled water, were procured for the study.

The study on Geopolymer concrete was primarily experimental, focusing on the use of 50%, 75%, and 100% fly ash as a source material with an alkaline solution (a combination of sodium hydroxide and sodium silicate) in 9 M and 12 M concentrations. Sodium-based solutions were preferred over potassium-based ones due to cost-effectiveness. M-25 and M-30 concrete mixes were designed as per IS 10262:2009, using 43-grade OPC, 20 mm coarse aggregate (IS 383:1970), and natural river sand passing through 4.75 mm sieves. The concrete was mixed manually, following conventional methods, ensuring proper bonding. After casting 150 mm x 150 mm x 150 mm cubes, they were cured at 35–45°C for 24 hours under laboratory conditions. Compressive strength tests were conducted at 7, 14, and 28 days to evaluate the performance of Geopolymer concrete.

Cement

In this work 43 grade cement is used with fly ash in different percentage i.e. 25%, 50% and 100%. The following table shows chemical properties of cement.

Table 1: chemical properties of cement

Oxides	**Percentage**
CaO	60-67
SiO2	17-25
Al2O3	3.0-8.0
Mgo	0.1-0.4
Alkalies (K2O, Na2O)	0.4-1.3
SO3	1.3-3.0

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Table 2: Fineness of Cement

Sr. No.	Wt. of sample (gm)	Wt. of residue (gm)	Fineness (%)	Avg. fineness
1	100 gm	8	8	6.50%
2	100 gm	6	6	
3	100 gm	8	8	
4	100 gm	4	4	

Table 3: Consistency of Cement

Sr. No.	% of water	Quantity of water (ml)	Penetration (mm)
1	26	106	10
2	27	109	12
3	28	114	21
4	29	118	23
5	30	122	24
6	31	123	31
7	32	126	32

The initial and final setting time is found to be 90 minutes and 270 minutes respectively.

Table 4: Physical Properties of Fly ash

Sr. No	Test Conducted	Test Results
1	CONSISTENCY	37.5
2	SPECIFIC GRAVITY(gm/cc)	2.54
3	FINENESS(Sq.m/kg)	586

Alkaline Solution

This study used a combination of sodium hydroxide and sodium silicate as the alkaline solution due to their cost-effectiveness and availability compared to potassium-based alternatives. Sodium silicate is available in different grades, while sodium hydroxide, with 97-98% purity, is commonly found in pellet form. To prepare the required concentration, both compounds are dissolved in water. Sodium hydroxide solution typically ranges from 8M to 16M, with 9M NaOH containing 360g of NaOH per liter. In this study, 9M and 12M sodium hydroxide solutions were used.

IV. RESULTS

The results of this study provide a comprehensive assessment of the compressive strength and performance of cement-free, fly ash-based concrete. By replacing 100% cement with fly ash and activating it with sodium silicate and sodium hydroxide, the study evaluates its structural feasibility.

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Table 5: Compressive strength for M25 & 9M solution

Percentage of Fly Ash	Compressive strength (Mpa)		
	7 Days	14 Days	28 Days
0	22.200	27.800	33.500
50	22.755	28.495	34.338
75	23.324	29.207	35.196
100	23.907	29.938	36.076

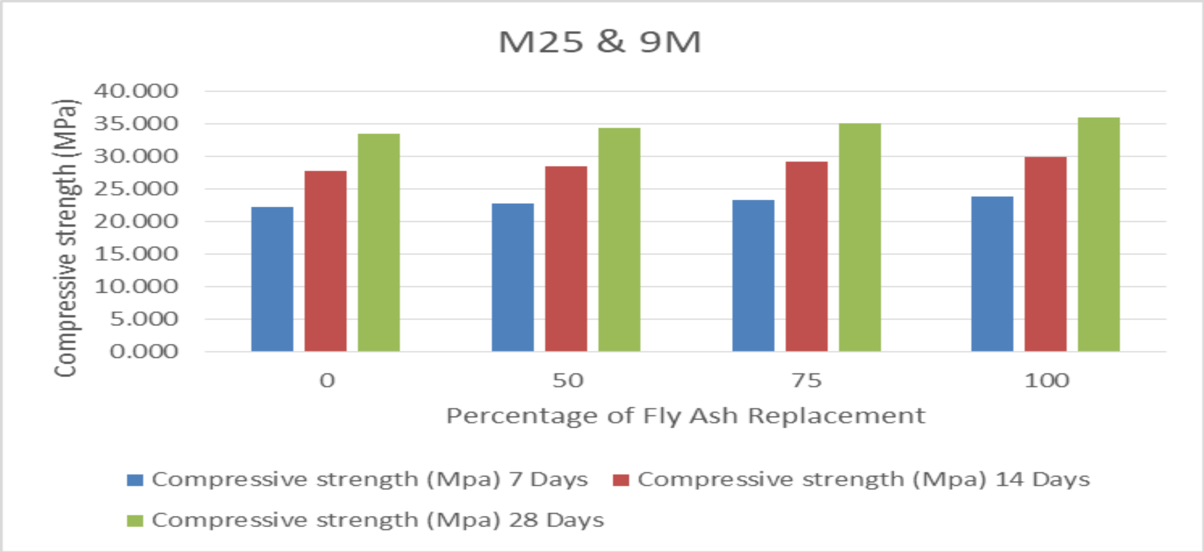

Figure 1: Compressive strength for M25 & 9M solution

Compressive strength is a crucial property of concrete. In this study, concrete cubes were cast and tested using 50%, 75%, and 100% fly ash as a binder, combined with an alkaline solution of sodium hydroxide and sodium silicate. The tests were conducted at 9M and 12M molarity to evaluate strength variations.

Table 6: Compressive strength for M25 & 12M solution

Percentage of Fly Ash	Compressive strength (Mpa)		
	7 Days	14 Days	28 Days
0	24.420	30.580	36.850
50	25.031	31.345	37.771
75	25.656	32.128	38.716
100	26.298	32.931	39.683

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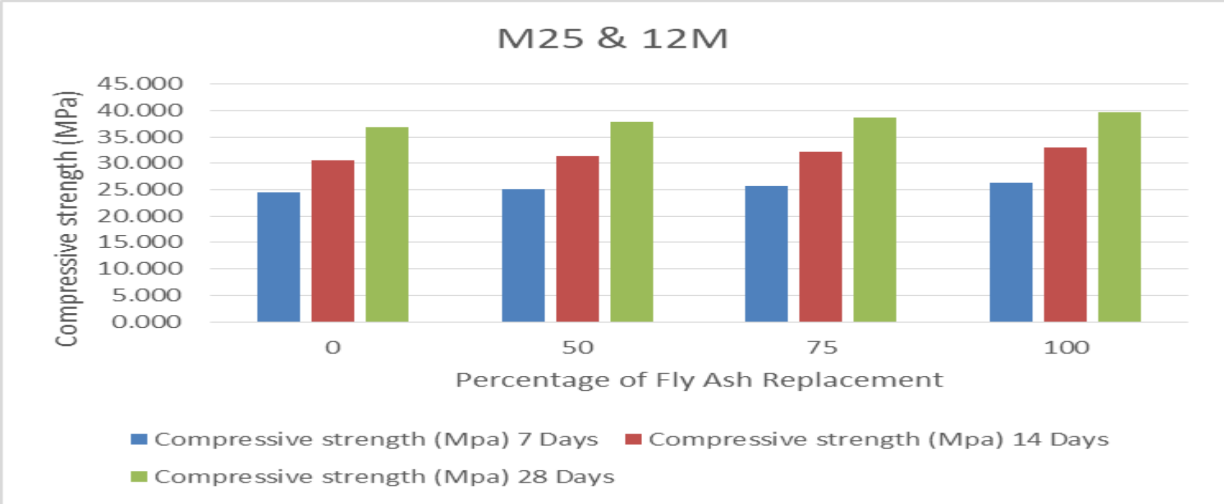

Figure 2: Compressive strength for M25 & 12M solution

The figure presents a combined graph of 7, 14, and 28-day average compressive strength for M-25 concrete with 12M solution. Results indicate that for M-25 with 9M solution, compressive strength surpasses the control mix by 33%, 7.19%, and 1.7% at 7, 14, and 28 days, respectively.

Table 6: Flexural strength for M25 & 12M solution

Percentage of Fly Ash	Flexural strength (Mpa)		
	7 Days	14 Days	28 Days
0	3.628	4.060	4.457
50	3.719	4.161	4.568
75	3.812	4.265	4.682
100	3.907	4.372	4.799

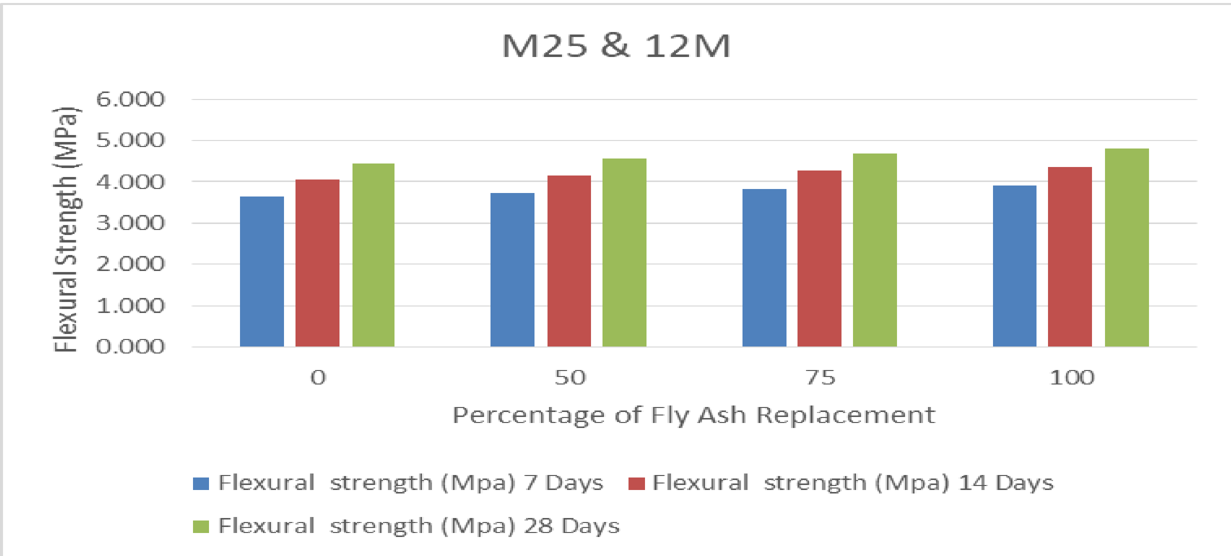

Figure 3: Flexural strength for M25 & 12M solution

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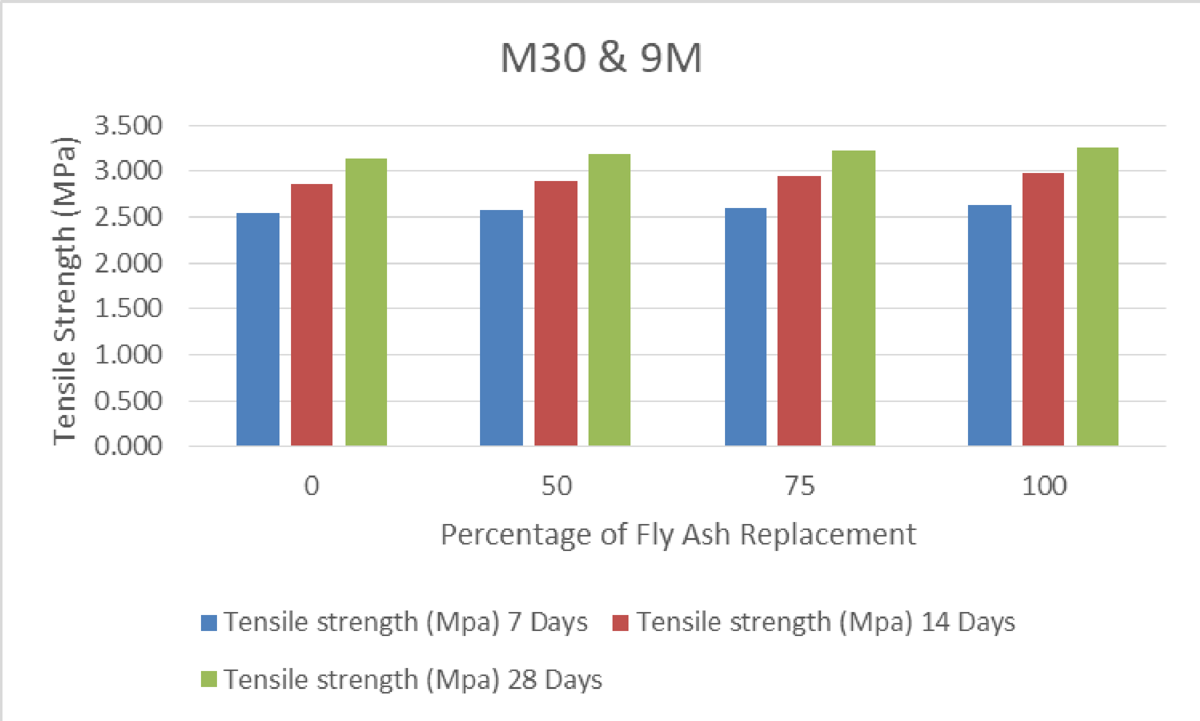

Figure 4: Tensile strength for M30 & 9M solution

V. CONCLUSION

This study demonstrates the feasibility of replacing 100% cement with fly ash in concrete, activated using sodium silicate and sodium hydroxide solutions. The experimental results indicate that fly ash-based concrete exhibits promising compressive strength, with variations observed based on molarity and curing duration.

For M-25 grade concrete, the use of a 9M solution resulted in strength gains of 33%, 7.19%, and 1.7% at 7, 14, and 28 days, respectively. Similarly, for M-30 concrete, the 9M solution led to increases of 35.6%, 7.12%, and 4.7%, while the 12M solution further enhanced strength by 41%, 19.2%, and 8.3% at the same curing intervals.

These findings confirm that cement-free, fly ash-based concrete, particularly with higher molarity alkaline solutions, can achieve comparable or superior strength to conventional concrete. This supports its potential as a sustainable alternative for structural applications, contributing to reduced environmental impact in construction.

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